TEMPO: Determining, Combining, and Predicting Earth Orientation Parameters for Spacecraft Navigation

by

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- **Navigating spacecraft in deep space requires accurate, real-time knowledge of the Earth's orientation**

- **The TEMPO program at JPL meets this requirement by twice-per-week:**

  - Measuring the Earth's orientation with VLBI
  - Combining the VLBI measurements with other data including atmospheric angular momentum analyses and forecasts
  - Delivering the resulting Earth orientation parameter estimates and predictions to the flight project navigation teams

EARTH ORIENTATION

- **Accurate navigation of spacecraft requires accurate, real-time knowledge of the Earth's orientation**
  - Must know Earth's orientation in space in order to determine the spacecraft's position in the navigation reference frame from Earth-based tracking measurements
  - Uncertainty in Earth's orientation can be a major, if not the dominant, error source in spacecraft navigation (Estefan & Folkner, 1995)
- **Earth's orientation in space given by 5 parameters:**
  - 2 precession-nutation parameters ($\Delta\psi$, $\Delta\varepsilon$)
    - **Specifies location of spin axis in celestial reference frame**
  - 2 polar motion parameters (PMX, PMY)
    - **Specifies location of spin axis in terrestrial reference frame**
  - 1 spin parameter (UT1)
    - **Specifies angle through which Earth has rotated about spin axis**
- **Earth's orientation varies rapidly and unpredictably**
  - UT1 changes particularly difficult to predict
    - **Rapid UTI changes caused primarily by exchange of wind-driven atmospheric angular momentum with the solid Earth**
    - **Predicting UT1 is as challenging as predicting atmospheric fluctuations (i.e., predicting the weather)**
  - In contrast, the precession-nutation, which is largely caused by the gravitational effect of the Sun, Moon, and planets upon the Earth, can be modeled and predicted to within 3 cm for periods up to a year in advance
    - **Model predictions rely upon past measurements**
- **Earth orientation measurements (polar motion, UT1) must be taken frequently and processed rapidly in order to maintain a real-time knowledge**

EARTH ORIENTATION REQUIREMENTS FOR S/C NAVIGATION

- **General Deep Space Network (DSN) requirement of:**
  - Real-time knowledge to within 30 centimeters (1-sigma) in each component (PMX, PMY, UT1)

    . 30 cm = 47.0 nanoradians = 9.70 milliarcseconds = 0.645 milliseconds

  - Post facto (prior to 14 days before present) knowledge to within 5 cm (1-sigma) in each component
    - **Post facto knowledge of Earth orientation can be more accurate than real-time knowledge due to:**
      - **utilization of other publicly available, but less timely, Earth orientation measurements**
      - **the ability to smooth the estimates by running the Kalman filter backward, as well as forward, in time**

- **Individual flight projects set their own requirements**
  - Typically, individual flight project requirements are consistent with above general DSN requirement
  - However, some flight projects require more accurate knowledge of the Earth's orientation
    - **Near Earth Asteroid Rendezvous (NEAR) requires:**

      real-time knowledge to within 17 cm (l-sigma) in each component

      post facto knowledge to within 5 cm (l-sigma) in each component
    - **Mars Pathfinder requires:**

      real-time knowledge to within 10 cm (l-sigma) in each component

      post facto knowledge to within 5 cm (1-sigma) in each component

SOURCES OF EARTH ORIENTATION DATA

- Space-Geodetic Techniques
  - Inertial Sources
    - Very Long Baseline Interferometry (VLBI)
    - Lunar Laser Ranging (LLR)
  - Non-Inertial Sources
    - Satellite Laser Ranging (SLR)
    - Global Positioning System (GPS)
- Proxy Length-of-Day Data
  - Atmospheric angular momentum (AAM)
    - Produced operationally by the National Centers for Environmental Prediction (formerly the National Meteorological Center—NMC)
  - AAM forecasts based upon a dynamical model of the atmosphere
- Accuracy of predictions are controlled by timeliness (and accuracy) of most recent measurements
  - UT1 varies rapidly and randomly
    - Stochastic process—uncertainty in our knowledge of UT1 grows from epoch of last measurement as $t^{3/2}$
  - TEMPO VLBI— twice-per-week, 48-hour turnaround
  - AAM— daily, 24-hour turnaround
  - AAM forecasts— five days into the future
  - Future GPS system— daily, 24-hour turnaround

TEMPO

- **Time and Earth Motion Precision Observations (TEMPO)**
  - Delivers Earth orientation calibrations to all JPL flight projects
  - Consists of 2 major components
    - **Earth orientation measurement component**
    - **Kalman Earth Orientation Filter (KEOF) component**

- **Earth orientation measurement component**
  - Single baseline VLBI measurements acquired twice-per-week using DSN telescopes
    - **Baselines used are Goldstone-Madrid (once-per-week) and Goldstone–Tidbinbilla (once-per-week)**
    - **Observing sessions are of 3-hour duration**
  - Data telemetered to JPL for rapid processing
    - **To compensate for loss in bandwidth incurred by telemetering data, the 70 meter antennae must be used for VLBI measurements**
  - Time to process VLBI data for Earth orientation parameters can be as fast as 24 hours, but is typically 48 hours
  - Single baseline VLBI measurements determine the baseline variation-of-latitude, UT0 components of the Earth's orientation
    - **Flight projects require polar motion, UT1**

TEMPO (cont.)

- **Kalman Earth Orientation Filter (KEOF) component**

  - A Kalman filter is used to combine the 2 independent single baseline VLBI variation-of-latitude and UT0 measurements to produce the polar motion and UT1 calibrations for delivery to flight projects

  - KEOF also incorporates other Earth orientation measurements that are publicly available, but less timely, in order to improve accuracy of post facto calibrations

    - **Polar motion measurements from satellite laser ranging**

    - **Polar motion and UTI measurements from multibaseline VLBI**

    - **UTI measurements from single baseline VLBI**

    - **Proxy LOD measurements from atmospheric angular momentum**

      - **AAM can be used as a proxy measure of LOD since the axial angular momentum of the atmosphere-solid Earth system is largely conserved**

    - **Proxy 5-day LOD forecasts from 5-day AAM forecasts generated by dynamical weather prediction models**

  - Various corrections are applied to the input data sets in order to assure their consistency prior to combination

    - **Bias-rate corrections are applied in order for data sets to be in alignment with each other and to be consistent with the IERS reference frame**

    - **Stated uncertainties are adjusted so that they more accurately reflect the "true" uncertainties of the measurements, not just internal precision**

  - Output of KEOF are the Earth orientation calibrations delivered to the flight projects

    - **History of Earth orientation based upon measurements to date**

    - **Short-term predictions of Earth orientation so that Earth orientation estimates are available to flight projects between Kalman filter runs (KEOF is currently run twice-per-week)**

TEMPO PRODUCTS

- VLBI measurements of baseline variation-of-latitude and UTO
  - Once-per-week on Goldstone-Madrid baseline
  - Once-per-week on Goldstone-Tidbinbilla baseline
  - Available about 2 days after epoch of each observing session
- Standby Timing Operation In Contingencies (STOIC) file
  - Contains Calibrations for polar motion and (1'11- UT (:
    - Size limited to 37 calibrations (records)
  - Available twice-per-week
- Earth Orientation Parameter (EOP) file
  - Contains calibrations for polar motion and UT1- UTC
  - Also contains precession-nutation parameters necessary to determine station locations in celestial reference frame at the few-centimeter level
  - Allows for arbitrary number of calibrations
    - Greater temporal resolution of calibrations means smaller interpolation error when interpolating between calibration values
  - Available twice-per-week

TEMPO PRODUCTS (cont.)

- **Annual smoothing (SPACE95, COMB95, POLE95)**
  - SPACE series of annual smoothings formed by using KEOF to combine the most accurate space-geodetic Earth orientation measurements available
    - TEMPO and other VLBI, lunar laser ranging, satellite laser ranging, and GPS measurements are combined
    - Resulting Earth orientation estimates (polar motion and UT1 –UTC) span 1976 to the present at 1-day intervals
  - COMB series of annual smoothings additionally incorporate Hit! optical astrometric measurements
    - Resulting Earth orientation estimates (polar motion and UT1–UTC) span 1962 to the present at 5-day intervals
  - POLE series of annual smoothings additionally incorporate ILS optical astrometric measurements
    - Resulting Earth orientation estimates (polar motion only) span 1900 to the present at 30.4375-day intervals
  - These annual smoothings are generated as part of the procedure employed when annually determining the corrections (to the set-i~s' bias, rate and stated uncertainties) that must be applied to the Earth orientation series used in the twice-per-week operations
    - The required corrections are determined by comparing each operational series to an independent reference series
    - The independent reference series must be created since no existing Earth orientation series is entirely independent of the data being corrected
    - The independent reference series are created by combining subsets of the series used to form the SPACE series
    - Combining all series then yields the SPACE series
  - Available once-per-year on or about March 15

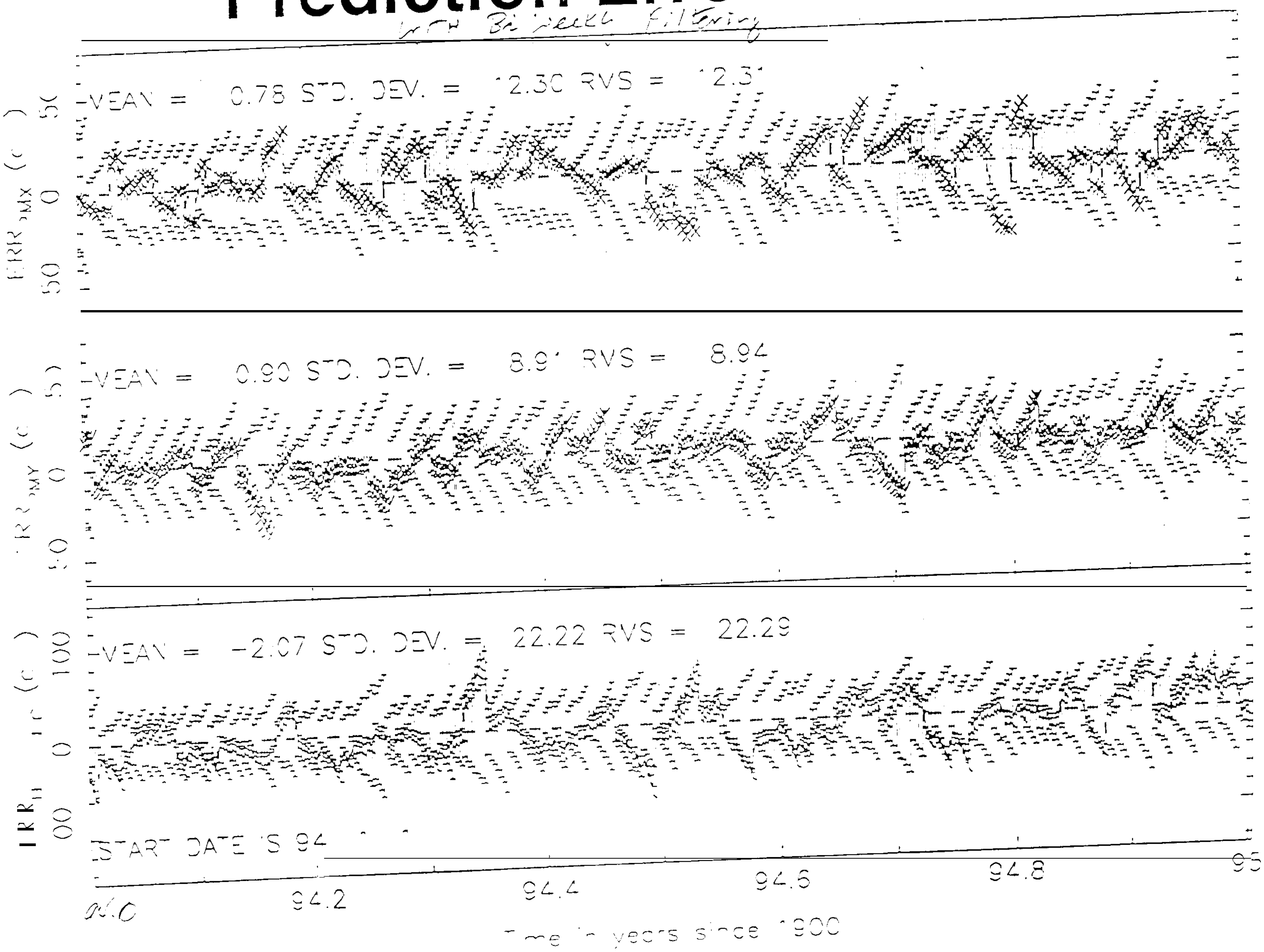
DATA VALIDATION AND QUALITY ASSURANCE

- **Data validation**
  - Real-time and short-term predictions of Earth orientation calibrations are validated after-the-fact by comparing them with more accurate values that become available after-the-fact
    - The more accurate, after-the-fact values are based upon additional measurements not available in near real-time
    - Real-time values accurate to within 8 cm for polar motion, 13 cm for UT1–UTC (rms accuracies during 1994)
    - 4-day predictions accurate to within 15 cm for polar motion, 29 cm for UT1–UTC (rms accuracies during 1994)
    - Therefore, must acquire and process Earth orientation measurements twice-per-week to meet a 30 cm real-time accuracy requirement
- **Quality assurance**
  - Maintaining Earth orientation calibrations within consistent IERS reference frame necessitates determination and subsequent application of series-specific bias-rate corrections
    - The values of the corrections are determined annually
    - They are then routinely applied twice-per-week during the KEOF run
  - Improvements to models and data (both accuracy and temporal resolution) necessitate changes to TEMPO to maintain accuracy of delivered calibrations
    - Use of new and improved models of ocean tidal effects on Earth orientation
    - Updating of stochastic models used within KEOF to describe the measurement process and noise
    - Incorporation of newly available data types such as GPS LOD measurements

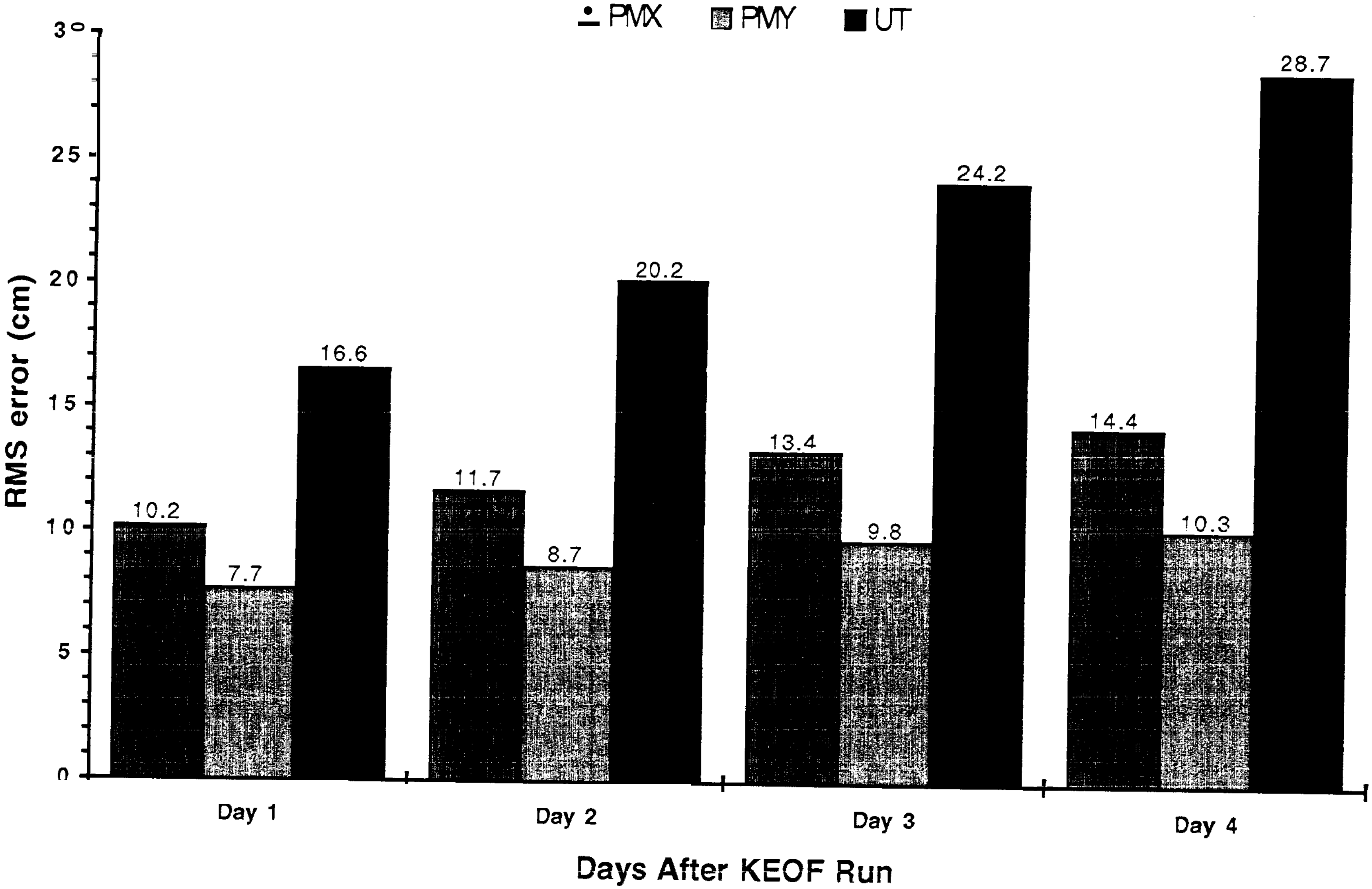
JPL

Prediction Error of UTPM

with Bi-weekly filtering



UTPM Prediction Error During 1994



FUTURE TEMPO SYSTEM

- **In FY97, TEMPO Earth orientation measurements will be acquired by a hybrid GPS–VLBI system**

- **Future GPS system**
  - Will provide near real-time (within 24 hours) measurements of polar motion and length-of-day (LOD)
    - **LOD is proportional to the time derivative of UT1**
  - LOD must be integrated to give UT1
    - **Integrated LOD will drift away from the "true" UT1**
  - VLBI measurements required to provide the benchmark UT1 values between which the GPS LOD values are integrated

- **Future VLBI system**
  - Timeliness and frequency of VLBI UT1 measurements can be reduced when near real-time GPS LOD values are available
    - **Use integrated LOD between VLBI UTI measurements**
  - Single baseline VLBI measurements will be acquired twice-per-month using DSN telescopes
    - **A factor of 4 reduction in frequency of VLBI observations**
  - Data will be recorded on tapes and express mailed to JPL for processing
    - **No longer need 70 meter antennae since data no longer telemetered**
    - **34 meter telescopes will be used instead**

- **Kalman Earth Orientation Filter**
  - Will be used to optimally combine the above GPS and VLBI measurements with other publicly available Earth orientation measurements to generate the Earth orientation calibrations that are delivered to the flight projects

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